Using evidence accumulation modelling to quantify the relative contributions of spatial

attention and saccade preparation in perceptual tasks.

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Abstract

A typical way to investigate the relationship between spatial attention and the programming of an eye movement is with a dual-task. Here, participants simultaneously make an eye movement in one direction and discriminate a target at the same or a different location. Results of these tasks consistently find that performance is best at the goal of an upcoming eye movement. It is less clear, however, the extent to which spatial attention can shift independently of the programmed saccade. In this paper, for the first time, we use an evidence accumulation model to examine this longstanding question. Specifically, across two studies, we quantify the relative contributions of spatial attention and saccade preparation in a perceptual dual-task. Our results establish that there is a unique and measurable effect of spatial attention away from the saccade goal, and, interestingly, that the relative magnitude of this effect varies by cue type. There is a larger influence of spatial attention when a peripheral rather than a central cue is employed. We suggest that these results support the claim that each form of orienting is mediated by a distinct underlying mechanism.

Keywords: visual attention, saccade, evidence accumulation model, saccadic programming, spatial cueing

Public Significance Statement: This study provides a new method by which to quantify the contributions of spatial attention and saccade preparation to perceptual tasks. Using evidence accumulation modelling, this study measures the magnitude of the spatial attention and saccade preparation effect in an orientation discrimination task. The results establish that both spatial cueing and the preparation of an eye movement uniquely contribute to task performance. The magnitude of these effects are found to vary by cue type, with a larger influence of spatial attention when a peripheral rather than central cue is employed. These results suggest that spatial attention and saccade preparation are mediated by distinct underlying mechanisms.

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The visual world is vast, complex and, without a filtering mechanism, would be computationally overwhelming. In order to make sense of what we see we must select and filter relevant visual information from irrelevant visual noise. Shifts of visual attention and eye movements both operate to achieve this purpose. Frequent, rapid eye movements, known as saccades, bring objects of interest onto our fovea, the part of our retina with the highest visual acuity. Visual spatial attention, on the other hand, can be oriented, without eye movements, to certain regions of space in order for information in those regions to be available for further processing (Posner, 1980). The extent to which these two forms of orienting are obligatorily coupled has been the topic of a longstanding debate. One particular task that is used extensively to investigate this question is the dual-task paradigm. In a classic dual-task, participants are required to saccade to one element in a display whilst simultaneously performing a discrimination task at the same (congruent) or a different (incongruent) location (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986). A typical finding is that immediately prior to the onset of an eye movement, discrimination performance improves at the goal of an upcoming saccade and deteriorates at other locations. This finding has led many authors to conclude that there is an obligatory shift in spatial attention that precedes all eye movements. What is less clear, however, is the extent to which spatial attention can influence performance away from the saccade goal. While some studies fail to report any influence of spatial attention during a dual-task (Deubel & Schneider, 1996; Deubel & Schneider, 2003; Hoffman & Subramaniam, 1995; Shepherd et al., 1986), the results of other research calls this conclusion into question (Born, Ansorge, & Kerzel, 2013;

Castet, Jeanjean, Montagnini, Laugier, & Masson, 2006; Deubel, 2008; Dore-Mazars,

Pouget, & Beauvillain, 2004; Kowler et al., 1995; Moehler & Fiehler, 2014, 2015;

Montagnini & Castet, 2007).

One way of addressing this longstanding issue is to quantify the relative contributions

of spatial cueing and saccade congruency to dual-task performance. Close inspection of the

literature, however, reveals that to date this has not been possible. The typical approach to

dual-task data has been to analyse accuracy and response times separately. While

informative, it is not possible using accuracy and RT alone to disentangle the influence of

orienting from other factors that can also influence perceptual decision-making. Here we

address this issue by using an evidence accumulation model to measure the influence of

spatial cueing and saccade congruency in a dual-task. The value of using a computational

approach is that it allows us to parameterise the decision-making process and, in turn, extract

a direct and comparable measure of orienting to task performance. This measure can be used

to assess the relative contributions of spatial attention and saccade preparation across

different dual-task conditions and distinct studies. Our results establish that there is an

independent and measurable influence of spatial attention away from the goal of a saccade

and that the magnitude of this effect varies by cue type.

Evidence accumulation modelling

It is typical in most two-alternative choice experiments for researchers to collect two

measures of performance; the proportion of correct responses and the speed of these

decisions. While it is common for these measures to be analysed separately, it is not clear

how to combine accuracy and RT into a single measure to quantify subject ability or task

difficulty (Wagenmakers, van der Maas, & Grasman, 2007). Consider for example the widely

reported speed-accuracy trade-off phenomenon (Ratcliff & Rouder, 1998). Here less cautious

responding is associated with faster and more error prone choices, while more cautious responding is associated with slower responding and greater accuracy even when difficulty and/or ability remains constant. If two participants, for example, respectively demonstrate this pattern of responding it is difficult to ascertain from accuracy and RT alone which participant has the superior ability, or if they differ at all in ability. This is because, without a theoretical basis to combine them, reaction times and accuracy are incommensurable. The same holds true if the goal is to compare difficulty across two different conditions and those conditions were presented in separate blocks. Here any effect of condition on difficulty cannot be disentangled from response caution, which may differ between blocks.

Evidence accumulation models provide a principled way of combining speed and accuracy, to enable direct insight into the processes that underlie decisions. They do so by combining accuracy and distribution of RT for correct and error responses to estimate parameters of a model that, in combination, can separate the effects of response caution and difficulty. While there are many different varieties of evidence accumulation models, they all share the same basic framework (Donkin, Brown, & Heathcote, 2009). These models assume that when making a decision a participant samples information from the environment and that information is used as evidence for one of the potential responses. As soon as evidence in favour of a particular choice reaches a threshold the decision process is terminated and the corresponding response is made. All these models provide estimates of three key parameters; the rate at which evidence for a response is accumulated (drift rate), how much evidence is required before a response is made (threshold) and the amount of time taken for non-decision aspects of the task, such as stimulus encoding and motor execution (non-decision time). These parameters quantify the latent variables that are assumed to underlie the decision-making process. Thresholds, for example, estimate the level of information necessary to make a response. As thresholds increase, responses take longer to produce but are more likely

to be correct. In this way, by allowing the threshold parameter to vary, the potential influence of a speed-accuracy trade-off can be accounted for. Drift rate, on the other hand, quantifies the deterministic component of the accumulation process (Wagenmakers et al., 2007). Estimates of this parameter reflect the quality of information in the system and can provide a direct and quantifiable measure of task difficulty or subject ability (Lewandowsky & Oberauer, 2018). Assessing how parameters vary as a function of experimental manipulations can reveal much more about the mechanisms that underlie decision making than is apparent from an analysis of accuracy and RT alone (Donkin et al., 2009). Take, for example, ageing research. A central finding in this area is that response times increase with age across a wide variety of tasks, such as lexical decision tasks (Salthouse, 1996). This finding has commonly been interpreted as evidence of an age-related cognitive decline. Ratcliff, Thapar and McKoon (2010), however, by fitting an evidence accumulation model, found that in contrast to this widely held belief, the mechanism underlying this effect was response caution. Older adults were more cautious responders, requiring more evidence to trigger a decision than young people. Critically there was no difference in mean drift rate, suggesting that older and younger people did not differ in their ability. Importantly, this conclusion was not apparent from a typical analysis of accuracy and response times, as in most cases accuracy was near ceiling and so the better accuracy associated with increased response caution was hard to detect.

Conclusions about the operation of spatial attention and saccade preparation during a dual-task have been limited in a similar way. This is because the dual-task paradigm necessitates that some experimental conditions, such as the direction and location of an eye movement, or the probability that a target will appear at a certain location, be held constant across blocks. When conditions are presented across separate blocks of trials, it is possible for participants to strategically adjust the level of information required to trigger a response.

For example, participants may require less evidence to make a decision when they are instructed to keep their eyes at fixation, relative to when they are directed to execute a saccade towards or away from the discrimination target. When accuracy and RT are used to measure the influence of orienting, the effect of response caution cannot be disentangled from task difficulty. As a consequence, to date it has not been possible to assess the relative contributions of spatial attention and saccade preparation to dual-task performance.

Dual-task paradigms.

A classic dual-task paradigm is designed to simultaneously manipulate both spatial attention and the direction of a programmed saccade. Typically, visual cues (Deubel, 2008; Dore-Mazars et al., 2004; Hoffman & Subramaniam, 1995) or probability schedules (Montagnini & Castet, 2007; Shepherd et al., 1986) direct spatial attention. Performance is then assessed when the target appears at the same (congruent) or a different (incongruent) location to the saccade goal, or at the same (valid) or a different location (invalid) to a spatial cue. Researchers typically take the difference in accuracy between the congruent and incongruent conditions as a measure of the saccade preparation effect and the difference in valid and invalid attention conditions, otherwise known as the cueing effect, as a measure of spatial attention. Discrimination performance is then compared for dual-task trials, discrimination-only trials and sometimes as a function of time.

Due to the difficulty of complying with instructions in these paradigms, it is common for some experimental conditions to be presented in separate blocks of trials. Which aspect of the task that is blocked varies greatly between studies. While some authors block the spatial attention manipulation (Born et al., 2013; Castet et al., 2006; Kowler et al., 1995; Montagnini & Castet, 2007; Shepherd et al., 1986), others hold constant whether and in what direction an eye movement is required (Deubel, 2008; Hoffman & Subramaniam, 1995). As outlined

above, in an analysis of discrimination performance the effects of spatial attention and saccade preparation cannot be disentangled from other factors, such as response caution, that can vary across blocked conditions. Hence, no study to date has been able to unambiguously quantify the contributions of these two orienting mechanisms. As a consequence, the extent to which spatial attention can influence performance away from the saccade goal remains largely unknown.

Some of the earliest studies that used the dual-task paradigm to investigate the relationship between attention and saccade preparation concluded that spatial attention was always obligatorily tied to the goal of a saccade. Sheperd and colleagues (1986), for example, required participants to saccade in the direction of a centrally presented arrow towards a placeholder positioned either to the left or right of fixation. Spatial attention was manipulated by varying the probability across blocks that the arrow indicated the likely location of an upcoming probe (80%, 50%, 20%). Participants had to execute an eye movement and detect the probe as quickly as possible, with probes remaining visible until response. On trials in which participants were required to simultaneously saccade towards a placeholder and detect the probe, probes were always detected faster at the goal of an upcoming eye movement, regardless of the probability that the target would appear there. In a no-move block, in which participants solely completed the detection task, expectancy was found to strongly modulate performance. These results led the authors to conclude, not only that spatial attention was tied to the saccade goal, but also that saccade preparation was a greater determinant of task performance than spatial attention. It is possible, however, that these effects were confounded by differences that may have occurred across blocks. A greater congruency effect on dual-task trials relative to the cueing effect on detection-only trials may reflect differences in orienting or the influence of response caution. The former would be theoretically important, the latter less so. Trials that simultaneously require both an eye movement and probe

detection may be associated with higher thresholds and hence greater accuracy, than detection-only trials. Critically, it is not possible using accuracy alone to tease apart these influences in order to unambiguously quantify and compare the magnitude of the saccade preparation and spatial attention effects. Similarly, as probes were visible until well after saccade onset it is possible that, rather than preparing an eye movement, participants overtly fixated the probe. Hoffman and Subramaniam (1995), in a refinement of this methodology, tasked participants to identify a target letter (T or L) amongst distractors (E or F). At the same time an auditory tone signalled that a saccade was required to one of four locations. Saccade direction was held constant while a centrally presented arrow indicated the likely location (75% valid) of an upcoming target. While the authors reported no influence of arrow validity in dual-task trials, they did find a typical cueing effect in the discrimination-only block. The magnitude of the saccade congruency effect was again reported to be greater than that of spatial cueing, but note how this conclusion comes from the comparison of accuracy rates across dual-task and discrimination-only blocks (see also Deubel & Schneider, 1996; Deubel & Schneider, 2003). Again, these kinds of cross-task comparisons make it difficult to isolate the influence of orienting from response caution in order to provide an accurate quantification of the magnitude of these effects. This is particularly apparent in a study by Kowler and colleagues (1995). Here, unlike in the previous studies, the authors found that the influence of spatial attention depended upon which aspect of the task was emphasised to participants. Spatial attention was found to influence performance away from the saccade goal, but only when participants were asked to concentrate on the discrimination only task.

More recent studies that manipulate spatial attention by varying the probability that a target will appear at a certain location in any given block are similarly limited. Montagnini and Castet (2007) for example, used a centrally presented arrow to direct saccades towards one of eight possible placeholders in a circular array. The probability that the discrimination

target, a Gabor patch, would appear at the saccade location or directly opposite to it was then manipulated across blocks (75%, 50%, 25%). In contrast to the results obtained by Sheperd and colleagues (1986), Montagnini and Castet found that in the block where the probability was low that the target would appear at the upcoming goal of a saccade (25%), discrimination performance was best at the location opposite the goal, but only for short arrow-target SOAs. Despite finding an effect where Sheperd did not, interpretation of this result is limited in a similar way to the Sheperd study. Because probability was separated across blocks, it is not clear how spatial attention modulated task performance. That is, the probability manipulation may have influenced performance because higher probability results in a greater allocation of spatial attention in that condition, or because higher probability blocks are associated with greater response caution, or some combination of both. As illustrated, this makes it difficult to draw unambiguous conclusions about the underlying source of these experimental effects. In a similar way to the studies reported above, the authors also attempted to compare the probability effect in dual- and single-task trials, despite these conditions being separated across blocks (see also Born et al., 2013; Moehler & Fiehler, 2014, 2015).

        Unlike studies that confound spatial attention with block, Deubel (2008) instead selected to hold the saccade goal constant. While spatial attention was manipulated with a 75% valid peripheral cue, a centrally presented arrow directed a saccade towards one of twelve possible placeholders. This location was held constant across separate blocks. Performance was also compared across a blocked dual-task and a separate no-saccade task condition. Therefore, while Deubel reported that discrimination was best at the peripherally cued location during the earliest stages of saccade preparation time and deteriorated the closer the target appeared to saccade onset in time, it was not possible to compare the relative magnitude of this effect to that apparent on the covert-only condition. Again, any difference

in the influence of spatial attention may be confounded by differences in response caution that may occur across dual- and single-task blocks.

It is clear from the studies reviewed above that much remains unknown about the extent to which spatial attention can influence performance during an eye movement. Part of the reason for this is that no study to date has been able to disentangle the influence of spatial cueing and saccade congruency from response caution. This has made it difficult to quantify and compare the relative contributions of each orienting mechanism within the same task, as well as across different tasks. In this paper, we use an evidence-accumulation modelling approach to address this issue. In particular, we use parameter estimates of an evidence accumulation model as a common currency by which to compare the influence of spatial attention and saccade preparation. In doing so, we are able to account for potential differences that may occur across blocked conditions and extract a direct, comparable and theoretically interpretable measure of spatial cueing and saccade congruency.

Current study

The aim of the present study was to use computational modelling to isolate and quantify the relative contributions of spatial cueing and saccade preparation during a dual-task. To this end across two experiments we combined evidence accumulation modelling with a modified version of the dual-task paradigm employed by Hoffman and Subramanian (1995). Participants were required to complete an orientation discrimination task whilst simultaneously programming and executing an eye movement to the same (congruent) or opposite (incongruent) location as the discrimination target. Spatial attention was directed in Experiment 1 through the use of a centrally presented arrow with 75% validity and in Experiment 2 with a sudden onset peripheral cue.

Consistent with Hoffman and Subramaniam's (1995) original study, saccade instruction was blocked. In Experiment 1, participants were instructed at the beginning of each block of trials to perform a saccade to a peripheral placeholder that was either at the location indicated by a centrally presented arrow, at the location opposite the arrow, or to maintain fixation (discrimination-only condition). In Experiment 2, participants were instructed at the beginning of each block to perform a saccade to the peripheral placeholder that was either on the left, right or above the fixation point. We employed two different cue types because they are likely to engage two distinct attentional mechanisms. Predictive centrally presented arrows, for example, are most likely to direct attention endogenously (but see Ristic & Kingstone, 2006; Ristic, Wright, & Kingstone, 2007), while sudden onset peripheral cues capture attention exogenously (Posner, 1980). Decades of research has suggested that these two modes of orienting likely engage distinct attentional mechanisms (Carrasco, 2011), and that each may have a unique relationship with oculomotor activity (Casteau & Smith, 2018; Smith & Schenk, 2012). We therefore used both cue types to direct attention. Unlike previous studies however, we used an evidence accumulation model to account for potential differences in response caution that may exist between blocked conditions.

We assessed the relative contributions of each orienting mechanism by fitting an evidence accumulation model, the linear ballistic accumulator (Brown & Heathcote, 2008), to data from the dual-task. In order to account for potential differences in response caution that can occur across blocked conditions, thresholds were allowed to vary by task instruction. Note here threshold specifically refers to threshold adjustments contingent on the nature of the stimulus on the current trial that affects decisions about that stimulus. Mean drift rate was used as our primary dependent measure by which to compare and quantify the magnitude of the spatial cueing and saccade congruency effects. Drift rates, but not thresholds, are widely

known to be influenced both by manipulations of spatial attention (Carrasco & McElree, 2001; Smith & Ratcliff, 2009; Smith, Ratcliff, & Wolfgang, 2004) and by the location and duration of gaze (Krajbich, Armel, & Rangel, 2010; Krajbich, Lu, Camerer, & Rangel, 2012; Krajbich & Rangel, 2011). Given these characteristics, we used the quality of drift rate as a measure by which to quantify the contributions of spatial attention and saccade congruency. By using a measure that can be isolated from other factors in the design that may affect performance, we were able to, for the first time, quantify and compare the magnitude of the spatial attention and saccade preparation effects across different experimental manipulations and different tasks for the first time. We therefore assessed how the relative contributions of spatial attention and saccade congruency varied by cue type.

Experiment 1

We had two specific hypotheses in relation to Experiment 1. First, we hypothesised that there would be an influence of both saccade congruency (Castet et al., 2006; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Krajbich et al., 2010; Montagnini & Castet, 2007) and spatial attention (Born et al., 2013; Castet et al., 2006; Kowler et al., 1995; Montagnini & Castet, 2007) on dual-task trials in our analysis of manifest measures (i.e., accuracy and RT). Given that previous studies have reported saccade congruency to have a larger influence on performance than spatial cueing (Shepherd et al., 1986), albeit by drawing conclusions across blocked conditions, we also predicted, that when quantified the relative magnitude of these effects would differ. Specifically, we predicted that saccade congruency would be a greater determinant of the quality of information accumulation than spatial cueing (Hoffman & Subramaniam, 1995; Sheperd et al., 1986).

Second, we hypothesised that there would be a robust cueing effect on discrimination-only trials. We predicted that once potential differences in thresholds were accounted for the magnitude of the cueing effect on discrimination-only trials would differ in magnitude from the effects evident on dual-task trials. Specifically, we predicted that the cueing effect would be smaller than the saccade-congruency effect, but similar to the cueing effect evident on dual-task trials (Montagnini & Castet, 2007).

Method

Participants.

Thirty-seven undergraduate students (8 male) from Macquarie University participated in Experiment 1 in return for course credit or remuneration (8 male; $M = 22$ years, $SD = 3.33$ years). Thirteen participants were excluded from any further analysis as they did not perform reliably better than chance.[1] All participants had normal or corrected to normal vision. Written informed consent approved by the local ethics committee was provided by each participant. Power simulations (Brysbaert & Stevens, 2018) were run with standard estimates taken from pilot data (saccade congruency $b = .26$, cue validity $b = .20$). These simulations revealed there to be sufficient power (80%) for an alpha level of .05 with a sample size of 24 participants.

Stimuli.

All stimuli were presented as white on a grey background. The fixation circle and arrow (1.45° in length) were presented at the centre of the screen. The location of saccade targets were indicated by six placeholder squares (2.58° x 2.58°) positioned around an imaginary circle with a radius of 6.19° from fixation. Three squares were positioned in the left visual field and a further three in the right visual field. In each visual field one placeholder was placed so that the centre of the placeholder was horizontal (0°) with the fixation circle, another placeholder was positioned at a 45° angle above the fixation circle and another at a 45° angle below the fixation circle (see Figure 1). The discrimination target was a horizontal or vertical Gabor patch (2.06° diameter) generated by modulating a sine wave (1.6 cycles per degree) with a Gaussian envelope. Distractors were diagonally (45°) oriented

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[1] A follow up analysis including all participants revealed a similar pattern of results. This suggests that the selection criteria did not drive our results.

Gabor patches, generated through the same procedure. Masks were created by overlaying two

diagonal Gabor patches with the same spatial frequency as the target and distractors.
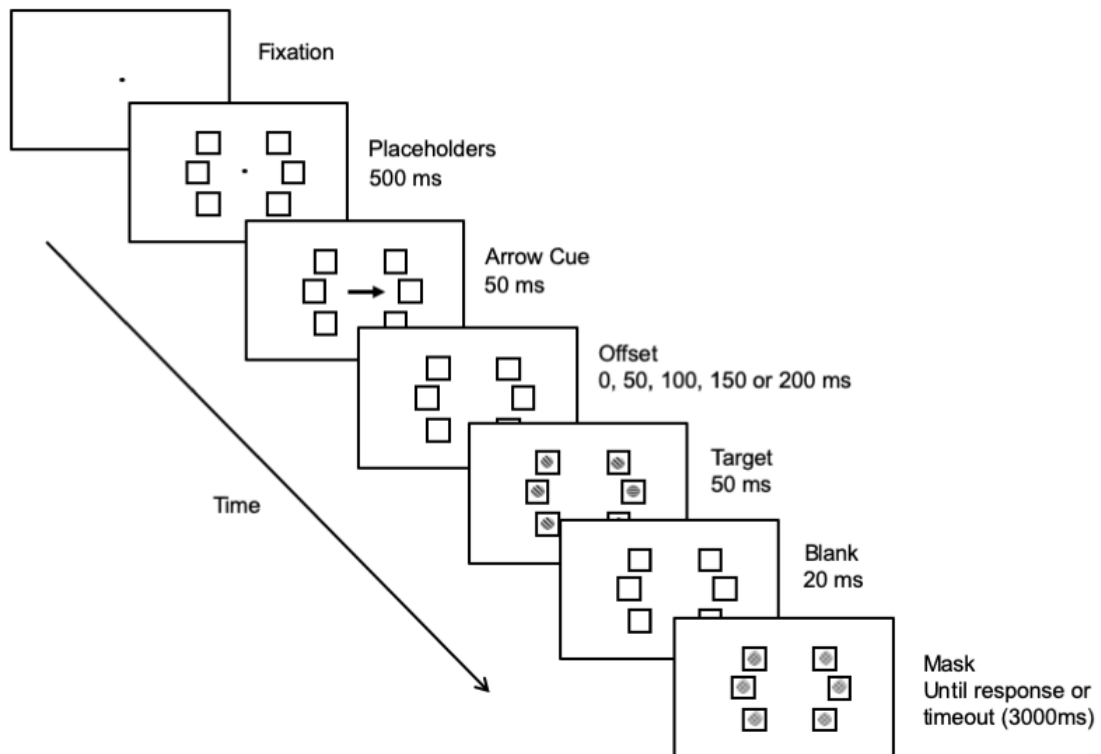
Figure 1. Schematic of Experiment 1 trial structure for a valid trial. Note that stimuli were presented as white on grey backgrounds.

Procedure.

Participants sat in a darkened room in front of a LED monitor (refresh rate 120Hz) positioned 85cm from the front edge of the desk. A chin and forehead rest stabilised the position of the participants head throughout the task. An Eyelink 1000 Desktop Mount Eye tracker (SR Research; 500Hz) placed on the desk monitored the gaze position of the participants right eye throughout the task. Each experiment began with 150 practice trials, followed by 100 trials of a QUEST staircase procedure where two interleaved staircases adjusted the contrast of the target and distractors to an 82% threshold (Watson & Pelli, 1983) while participants maintained central fixation. The contrast value at the end of this procedure was maintained throughout the main experiment. The main experiment consisted of 720 trials. The experiment followed a 3 x 2 x 5 factorial design. Saccade congruency had three levels (congruent, incongruent, no saccade). Cue validity had two levels (valid, invalid). As previous studies have suggested that the spatial cueing effect may vary across SOA and saccade preparation time, we manipulated the time between arrow and target onset to include five levels of SOA (50, 100, 150, 200, 250ms)[2].

Trial structure.

To begin each trial participants were required to maintain fixation on a small white circle in the centre of the display and press the space bar. The first frame displayed six placeholder squares for 500ms. After this the fixation circle was replaced by an arrow pointing to one of the placeholders for 50ms. Participants were instructed to make one of three eye movements upon the onset of the arrow. Make a saccade towards the placeholder

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[2] Preliminary analysis revealed that a large portion of trials in the 250ms condition had to be excluded due to participants performing a saccade before target offset (40% of trials in that condition). Analysis revealed that the exclusion of these trials did not significantly alter results and therefore these trials were excluded from all subsequent analyses.

indicated by the arrow, in the opposite direction to the arrow or not to make a saccade. These instructions were blocked and the order of blocks was counterbalanced across every 6th participant. Arrow-offset was followed by the placeholders on display for a period of 0, 50, 100, 150 or 200ms creating five SOA conditions respectively (50, 100, 150, 200 and 250ms). The discrimination target then appeared in one of the six placeholders for 50ms. On three quarters of trials the target appeared at the placeholder indicated by the arrow, on the remaining quarter it appeared at the placeholder directly opposite the arrow. Participants were aware of the arrow's validity. Distractors appeared in the remaining placeholder locations. After a 20ms period following target offset, six plaid masks then appeared in all placeholder locations until the response or time out.[3] Participants had 3000ms to respond by pressing the up or down key, with response key counterbalanced across participants. Participants received two types of visual feedback. "Correct" or "Incorrect" indicated whether the correct orientation discrimination decision was made, while the colour of the feedback (red or green) indicated if the correct eye movement had been made. Additionally, if no saccade was detected within 750ms of the go-signal participants received the feedback "too slow."

Eye movement data analysis.

Eye movements were monitored both online and offline. Online monitoring of eye movements ensured that participants maintained fixation until the onset of the arrow. If the eye moved more than 1.45° away from fixation before the onset of the arrow the trial was terminated and represented, in random order, at the end of each block of trials. On trials that required an eye movement, correct saccades were defined as those that landed within the correct placeholder. In the no saccade condition trials where the eye moved more than 1.45°

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[3] Pilot testing revealed that completion of this task was not possible without a brief 20ms gap between target offset and mask onset.

away from fixation were classified as errors. Gaze data was analysed offline to detect the

onset of saccades. At each time point raw eye position data was smoothed with a Gaussian.

The average velocity of five neighbouring time points was then used to compute a smoothed

average eye velocity. Saccades were detected when eye velocity exceeded the median

velocity by more than 5 SDs for at least 8ms, a standard criterion in eye tracking studies

(Engbert & Kliegl, 2003; Li, Barbot, & Carrasco, 2016). Trials containing blinks, incorrect

saccades or eye movements initiated before the offset of the target were eliminated. Only

trials in which the eyes were at fixation while the target was onscreen were compared. As is

typical in dual-task studies, any trial where an eye movement was initiated before target

offset or more than 450ms after target offset was eliminated (Born et al., 2013; Castet et al.,

2006; Moehler & Fiehler, 2014, 2015).

Results

In addition to our modelling analysis, we briefly assessed the influence of saccade congruency and spatial cueing on three manifest measures: proportion of correct discrimination responses, time between target onset and button press (RT) and saccade latency, the time between arrow and saccade onset. These results were analysed with linear mixed effects modelling (LMM) implemented using software package lme4 (Bates, Maechler, Bolker, & Walker, 2015). The reliability of each effect of interest was evaluated using an incremental modelling approach in which goodness of fit statistics (AIC, BIC and Log Likelihood values; Akaike, 1974; Schwarz, 1978) were used to determine which of our models provided the best fit to our data. As is typical in dual-task studies we also analysed our results as a function of time between target offset and saccade onset (Born et al., 2013; Deubel, 2008). As absolute time was not found to interact with either saccade congruency or cue validity, we include this analysis in supplementary materials. Any trial in which RT exceeded 3SDs of the participant's mean were trimmed from the analysis (1.0%).

Manifest Analysis.

Dual-task trials.

Accuracy. A mixed effects model with a binomial distribution and logit link function was used to assess accuracy. The incremental model comparison procedure revealed that including the main effects of saccade congruency ($\chi^2(1) = 193.27$, $p < .001$) and cue validity ($\chi^2(1) = 39.07$, $p < .001$) both significantly improved the fit of the model, and therefore both terms were included in the final model. Accuracy was better when the saccade goal and discrimination target were congruent ($M = 0.80$, $SD = 0.17$, $b = 0.82$, $SE = 0.06$, $z = 13.60$, $p < .001$), relative to incongruent ($M = 0.66$, $SD = 0.19$). Accuracy was also better when the

arrow was valid ($M = 0.76$, $SD = 0.17$; $b = 0.41$, $SE = 0.07$, $z = 6.32$, $p < .001$) relative to

invalid ($M = 0.70$, $SD = 0.20$) (see Figure 2A).

Reaction time. The best model of RT included a main effect of saccade congruency

($\chi^2(1) = 86.51$, $p < .001$), cue validity ($\chi^2(1) = 19.96$, $p < .001$), SOA ($\chi^2(3) = 145.47$, $p <$

.001) and a significant Saccade Congruency x Cue Validity interaction ($\chi^2(1) = 32.16$, $p <$

.001). Compared to trials with an SOA of 50ms, RTs were faster in all other SOA conditions.

The model also revealed the saccade congruency effect to vary as a function of cue validity.

To follow this up two FDR adjusted paired t-tests revealed that for trials where the arrow was

valid, RTs were significantly slower when the target and saccade goal were incongruent

relative to congruent ($t(23) = 2.90$, $p = .02$). There was no significant effect of saccade

congruency when the arrow was invalid ($t(23) = 0.27$, $p = 0.80$).

Saccade latency. An LMM with saccade latency as the dependent variable revealed

the model of best fit to include a main effect of saccade congruency ($\chi^2(1) = 223.77$, $p < .001$)

and a significant Saccade Congruency x Cue Validity interaction ($\chi^2(1) = 268.57$, $p < .001$).

As can be seen in Figure 2C, saccade latencies were slower on trials where the saccade goal

conflicted with the direction of the arrow. That is, participants were slower to initiate eye

movements in the opposite direction to the arrow compared to the same direction. We explore

this finding below by fitting the saccade latency data with an LBA model.

Discrimination-only trials.

Analysis of discrimination-only trials revealed the best model of accuracy to include a

main effect of cueing ($\chi^2(1) = 118.34$, $p < .001$). Accuracy was higher when the arrow was

valid ($M = 0.85$, $SD = 0.11$, $b = 0.96$, $SD = 0.09$, $z = 11.08$, $p < .001$) relative to invalid ($M =$

0.69, $SD = 0.17$). The best model of RT likewise revealed a main effect of cueing ($\chi^2(1) =$

58.24, $p < .001$) and SOA ($\chi^2(3) = 73.04$, $p < .001$). Response times were faster when the cue

was valid (*M* = 739, *SD* = 114; *b* = -59.10, *SE* = 7.80, *t* = -7.58) relative to invalid (*M* = 800,

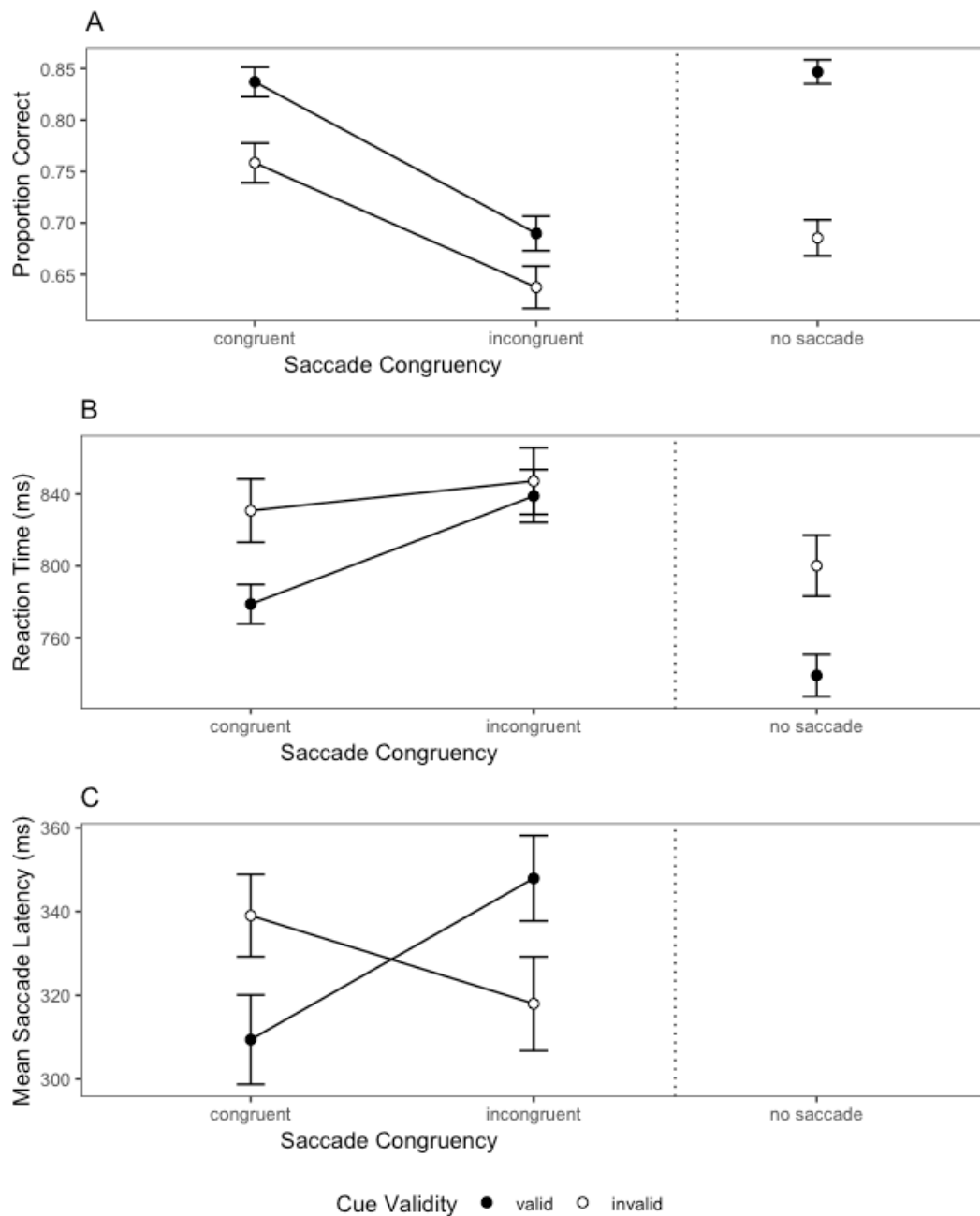*SD* = 166). RTs were also faster on trials with short SOAs compared to long SOAs.

Figure 2. Experiment 1 mean (A) proportion correct, (B) reaction time and (C) saccade latency as a function of saccade congruency and cue validity. Note error bars in all figures represent within subject standard errors.

Linear Ballistic Accumulator Analysis.

   Model specification.

   In order to quantify the influence of spatial attention and saccade congruency we fit

the linear ballistic accumulator (LBA) to each participant's data. LBA models have one

accumulator for each response, each with potentially different parameters values. Therefore,

there was an accumulator for both horizontal and vertical targets. Each accumulator

possessed the following parameters: start point noise, representing the range of evidence

values in each accumulator before the beginning of the decision, which was assumed to

follow a uniform distribution with a range of 0 to $A \geq 0$; the rate at which evidence is

accumulated, known as the drift rate, which was assumed to follow a normal distribution with

a mean of v and a standard deviation of $s_v \geq 0$; the amount of evidence necessary to make a

decision, or response threshold, denoted by b (note that the results in our analysis reported in

terms of the difference between the top of the start point distribution and the response

threshold, $B = b - A \geq 0$); and a non-decision time parameter, $T_{er} \geq 0$, which we assumed to

be the same for both accumulators (Donkin, Brown, & Heathcote, 2011; Heathcote, Brown,

& Mewhort, 2002).

   To describe LBA parameterization, a response accumulator factor "R" was defined,

with levels corresponding to the horizontal and vertical accumulators, and an accumulator

correspondence factor, "C", denoting the "true" (matching) and "false" (mismatching)

accumulators for a particular stimulus. If the stimulus was horizontal, for example, then the

horizontal accumulator was designated the "true" accumulator and the vertical the "false"

accumulator. Importantly, the difference between the drift rates for the true and false

accumulator was a measure of the quality of information accumulation (Boag, Strickland,

Loft, & Heathcote, 2019). This difference was, therefore, the main dependent measure by

which we measured the influence of orienting. Response bias was modelled by allowing B to

vary with the response factor. Above-chance performance requires a higher evidence accumulation rate for the true than false accumulator and this was modelled by allowing v to vary with the correspondence factor.

We fit the model to dual-task trials and discrimination-only trials separately, but compared parameter estimates between the models. In dual-task trials thresholds were allowed to vary as a function of saccade instruction, while drift rate was allowed to vary by saccade congruency, cue validity and SOA. For discrimination-only data we allowed the drift rate parameter to vary by cue validity and SOA. Across both models the s_v parameter was allowed to vary with the correspondence factor (see Heathcote & Love, 2012), and s_v for the mismatching parameter was fixed at 1 to make the model identifiable (see Donkin et al., 2009). We estimated a single value for all conditions of A and T_{er}.

Model fit.

Separate model fits to each participant's data were obtained using maximum likelihood estimation. We used the optimization (parameter search) method to obtain fits, fitting models with fewer parameters and then use the best fitting parameters for the simple models as starting points for the best fitting parameters of more complicated models (Donkin et al., 2011). Graphical summaries, included in supplementary materials, confirmed that our selected models were able to capture the major trends in the data (Heathcote et al., 2002).

Parameter estimates.

Thresholds. First, threshold estimates (B) were assessed using a LMM which included an effect of blocked saccade instruction (with arrow, against arrow, no saccade) and response (horizontal or vertical). The model of best fit included a main effect of saccade instruction ($\chi^2(2) = 43.11$, $p < .001$). Thresholds were lower on trials that did not require an

eye movement relative to when a saccade was required in the same direction as the arrow (b = 0.65, SE = 0.11, t = 5.73) or in the opposite direction (b = 0.75, SE = 0.11, t = 6.64) (2.2 v 2.9 v 3.0). A pairwise t-test revealed that there was no evidence to suggest that thresholds differed whether the eye movement was in the same or opposite direction to the arrow ($t(23)$ = -1.31, p = .20).

Drift Rate. We took the quality of information accumulation, the difference between the true and false drift rate (C), as the measure by which to compare the influence of spatial cueing and saccade congruency. In order to compare the magnitude of these effects we first confirmed that both saccade congruency ($\chi^2(1)$ = 101.64, p <.001) and spatial cueing modulated the quality of information accumulation ($\chi^2(1)$ = 6.87, p = 0.009) on dual-task trials and spatial cueing had the same influence on discrimination-only trials ($\chi^2(1)$ = 67.26, p < .001) (see supplementary materials for full LMM results). We then extracted a single comparable index of the quality of accumulation. We first collapsed across SOA, and then computed the difference between the true and false drift rate across each level of saccade congruency and cue validity. That is, to calculate the magnitude of the saccade congruency effect we computed, for each participant, the difference in true and false drift rates on trials in which the saccade goal was congruent with the target vs. incongruent with the target. The same calculation was made for valid vs. invalid trials. The results revealed the effect of saccade congruency (0.78) to be four times as large as the effect of spatial cueing (0.20) on dual-task trials (see Figure 3). An FDR-adjusted t-test confirming that this difference in magnitude was significant ($t(23)$ = 2.46, p = 0.03). We then compared the magnitude of the dual-task effects to those on discrimination-only trials. The influence of spatial cueing on discrimination-only trials was revealed to be five times as large as that evident on dual-task trials (0.99; $t(23)$ = -3.53, p = .005). There was no evidence to suggest that the magnitude of this effect differed in size from the saccade congruency effect ($t(23)$ = -0.98, p = .34).
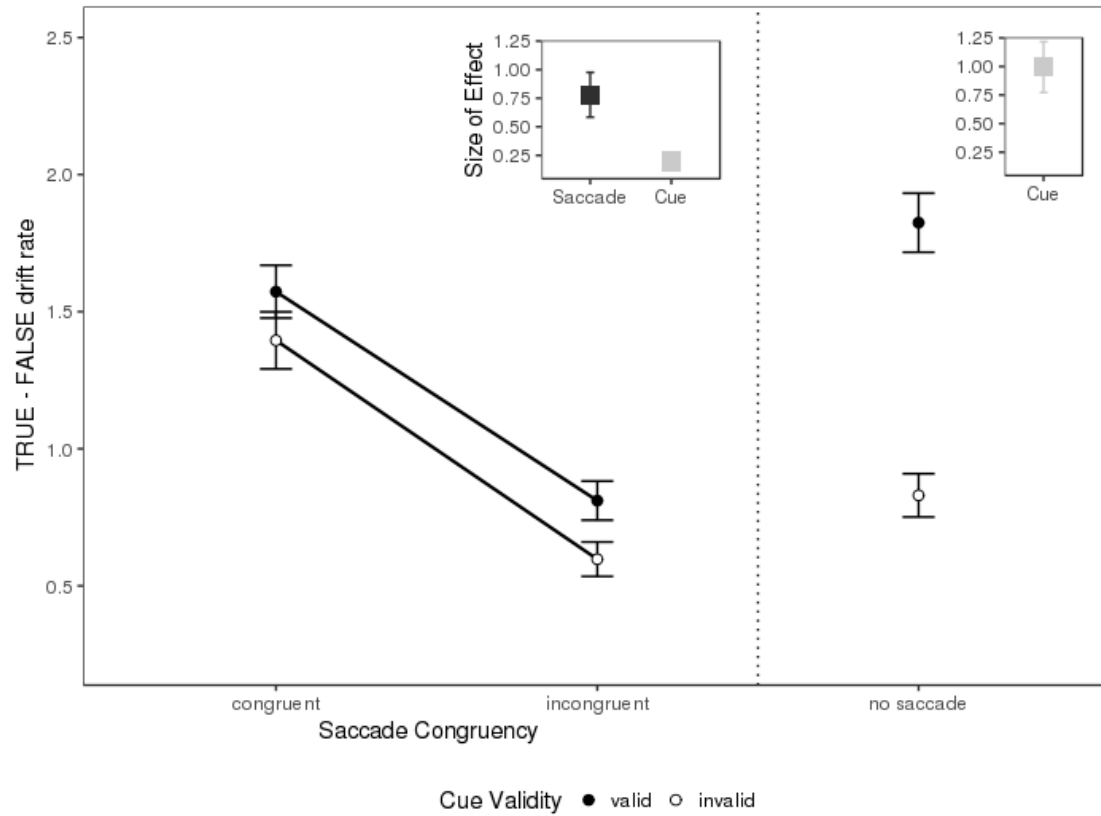
Figure 3. Difference between true and false drift rate for saccade congruency and cue validity in Experiment 1. Left side of the graph shows the effects for dual-task trials and the right side of the graph shows the effects for discrimination-only trials. Insets show the magnitude of the saccade congruency and spatial cueing effect.

LBA Saccade Latency Analysis

Our manifest analysis revealed a significant interaction between spatial cueing and saccade congruency in saccade latencies. That is, eye movements were faster when initiated in the same direction as the arrow, relative to in the opposite direction to the arrow. It is difficult to characterise the nature of this interaction from latencies alone. For example, at first glance this interaction suggests that there is some kind of obligatory coupling between spatial attention and saccade preparation. However, an alternative interpretation is that this effect may not have perceptual consequences, but rather be due to a bottleneck in the motor execution of an eye movement that occurs when there is a conflict between saccade instruction and arrow direction (Kuhn & Benson, 2007; Kuhn & Kingstone, 2009). That is, when there is no conflict between the saccade goal and the spatial cue saccades are rapid to initiate. When however, the saccade goal and spatial cue conflict latencies are much slower to initiate because there is a bottleneck in the execution of the eye movement that must first be resolved.

To explore these possibilities, we fit an LBA model to each participant's saccade latency data. The model had only a single accumulator corresponding to the correct movement as only correct eye movement trials were included in the results, and so there was no data to constrain estimates associated with the incorrect accumulator. If the conflict effect is best characterised as a bottleneck then we would expect the conflict to be apparent in the non-decision time parameter of the model, as this parameter quantifies the duration of all processes that occur outside the decision itself. If, however the effect is better characterised as a perceptual yoking between orienting mechanisms then we would expect the conflict effect to manifest in the drift rate parameter. Note that it can be assumed that thresholds did not differ between cue-congruent and cue-incongruent conditions as these were not blocked and so participants could not adjust their caution as a function of cue-congruency.

Model specification.

We fit a model that allowed both non-decision time (T_{er}) and mean drift rate (v) to vary with cue congruency. That is, whether the spatial cue and saccade goal coincided (cue-congruent) or not (cue incongruent). A single value was estimated for all conditions of A and B and we fixed $s_v=1$ to make the model identifiable.

Model fit.

The maximum likelihood model estimation software we used does not allow for fitting a single accumulator, so we moved to the more flexible DMC software (Heathcote et al., 2018) which carries out estimation in a Bayesian manner. We outline the priors and sampling procedure used in supplementary materials. Sampling occurred in two steps. In the first step sampling was carried out separately for individual participants. The results of this step were then used as starting points for the full hierarchical model, whose results are reported below. Model fit was excellent and cumulative distribution functions can be seen in supplementary materials.

Parameter estimates.

Parameter estimates are reported as posterior medians with 95% credible intervals given in square brackets. We test the effects of cue-congruency using Bayesian p-values (Klauer, 2010) to test differences in parameters between conditions by tabulating differences between pairs of parameters from the cue-congruent and cue-incongruent conditions. The p values corresponded to the proportion of differences where congruent was greater than incongruent (for T_{er}) or incongruent was greater than congruent (for mean rates). Hence, small p values support better performance in the congruent condition. Non decision time (T_{er})

was 0.02 s faster in the congruent condition than the incongruent condition (0.072 s [0.067, 0.077] vs. 0.092 s [0.087, 0.097], *p < .001*). Mean rate was also higher in the congruent condition (5.34 [5.21, 5.47] vs. 5.00 [4.87, 5.12], *p* < .001) than the incongruent condition.

Discussion

In Experiment 1 we sought to measure the magnitude of the spatial cueing and saccade congruency effects in a dual-task. To do so, we modified the typical dual-task paradigm (Hoffman & Subramaniam, 1995). A centrally presented arrow (75% valid) was used to direct spatial attention and blocked saccade instruction was used to manipulate the direction of a programmed saccade. Unlike previous studies, however, an evidence accumulation model was fit in order to extract a direct and comparable measure of spatial attention and saccade preparation. Our results establish that there is a measurable and independent contribution of both types of orienting in the dual task, but that the relative magnitude of these effects differ.

Consistent with our first hypothesis the results revealed both spatial cueing and saccade congruency to influence performance in our manifest analysis. Accuracy was higher when the saccade goal and discrimination target coincided (congruent) relative to when they were orthogonal (incongruent). This finding is consistent with previous studies that report performance to be enhanced at the goal of an upcoming eye movement (Born et al., 2013; Deubel, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Moehler & Fiehler, 2014, 2015; Shepherd et al., 1986). Spatial cueing was also found to influence performance. Accuracy was higher when the arrow correctly indicated the upcoming target location, relative to when it did not. Again, this finding is in line with a growing number of studies that find an influence of spatial attention away from the saccade goal (Born et al., 2013; Deubel, 2008; Dore-Mazars et al., 2004; Kowler et al., 1995; Moehler & Fiehler, 2014, 2015; Montagnini & Castet, 2007). Neither of these effects were found to vary by SOA. While somewhat surprising, as some studies report a larger cueing effect at short cue-target SOAs (Montagnini & Castet, 2007), other authors have failed to find evidence of this interaction (Born et al., 2013; Moehler & Fiehler, 2014; Van der Stigchel &

de Vries, 2015). This discrepancy may be due to the manner of target and distractor presentation. In the present experiment, and those that do not find any modulation in orienting effects across time, target and distractors were presented abruptly. It is possible that this onset creates a sustained attentional influence that may mask differences evident across time (Van der Stigchel & de Vries, 2015). Our analysis of RTs revealed a significant interaction between saccade congruency and cue validity. As this finding was not expected we assess whether it replicates in Experiment 2.

Importantly, we followed the manifest analysis by fitting an evidence accumulation model to the data. We used the quality of evidence accumulation as a measure by which to compare the influence of cue validity and saccade congruency. The results revealed that the saccade congruency and spatial cueing effects differed in magnitude. The influence of saccade congruency was approximately four times as large as that of spatial cueing. This finding suggests that saccade preparation contributed more strongly to successful performance in the dual-task than spatial attention. Importantly however, regardless of which direction an eye movement had been programmed, the validity of a spatial cue still made a measurable contribution to task performance.

In relation to our second hypothesis there was a robust cueing effect evident on discrimination-only trials (where subjects did not move their eyes). Modelling revealed that participants required less evidence to trigger a response in these trials relative to trials that required an eye movement. In accounting for this threshold difference for the first time, we were able to unambiguously compare the influence of orienting across dual-task and discrimination-only trials. Interestingly, the magnitude of the spatial cueing effect in discrimination-only trials was five times as large as the cueing effect evident in dual-task trials. It did not however, significantly differ in size from the saccade congruency effect. It is possible that because participants were required to maintain central fixation on these trials,

they nonetheless covertly prepared but never executed an eye movement in the same direction as the arrow.

Finally, our results revealed that there was an interaction between cue validity and saccade congruency in saccade latencies. That is, saccade latencies were slower when the saccade goal and centrally presented arrow were incongruent, relative to when they were congruent. This finding is consistent with a number of previous studies that find saccade latencies to be faster when a centrally presented arrow or gaze cue is congruent to the saccade goal, relative to incongruent (Hermans & Walker, 2012; Kuhn & Benson, 2007; Kuhn & Kingstone, 2009; Ricciardelli, Bricolo, Aglioti, & Chelazzi, 2002). LBA modelling allowed us to tease apart and characterise the nature of this effect. Our results revealed that the conflict effect was manifest in both drift rate and non-decision time. This finding suggests that the conflict between arrow direction and saccade location influenced both the perceptual aspects of the task and the motor execution of an eye movement. It is possible that the conflict effect was manifest in drift rates because, by virtue of being the go-signal for an eye movement, the arrow itself contained an inherent conflict. That is, participants were required to interpret the arrow for both saccade direction and likely location of the upcoming target. This may have inadvertently yoked saccade preparation and spatial attention, hence producing the rate effects.

The non-decision time effect, however, suggests that this yoking cannot provide a full account of the conflict, and instead points to the possibility that there is a bottleneck in the execution of an eye movement. That is, when the cue location and saccade goal align saccade latencies are fast. When, however, the spatial cue appears opposite the saccade goal there is a conflict which must be resolved before a saccade can be executed. On this account the conflict effect that arises when cue location and saccade goal are in opposition would affect

the execution of a prepared saccade but not the perception of the target. We address this

possibility by uncoupling the saccadic go-signal from the spatial cue in Experiment 2.

Experiment 2

In Experiment 1 we established that both saccade congruency and spatial attention, guided by a centrally presented arrow, had a measurable impact on dual-task performance. The results revealed the relative magnitudes of these effects to differ, with saccade congruency being a greater determinant of performance than spatial attention. In Experiment 2 we assess whether this holds true when spatial attention is directed by a peripheral cue. Here, the centrally presented arrow is replaced with a sudden onset/offset peripheral cue. In Experiment 1 spatial attention and saccade direction were both indicated by the same cue. In Experiment 2 we overcome this limitation by directing saccades with blocked instruction and an auditory tone. Finally, we introduce a third possible target location. Unlike in Experiment 1, where the target always appeared at the goal of a centrally presented arrow or directly opposite to it, in Experiment 2 the target was equally likely to appear at any one of three possible placeholder positions, positioned to the left, right and above fixation. Each position was also equally likely to be cued.

The introduction of a third placeholder position enabled us to examine the extent to which the saccade congruency and spatial cueing effects are spatially distributed. While some studies suggest that the preparation of an eye movement can benefit performance at locations neighbouring the saccade goal (Castet et al., 2006), other research has suggested that these effects are focal (Deubel & Schneider, 2003). If the benefit of preparing an eye movement is spatially distributed then performance should vary as a function of the angle between saccade goal and target location. Specifically, we expect performance to be worse when the saccade goal is at an angle of 180° from the target (opposite) compared to an angle of 90°. The same would hold true if spatial cueing effects were distributed. In using evidence accumulation modelling we are able to isolate the influence of orienting on decision making, and for the

first time, compare the relative contributions of spatial attention directed by a peripheral vs.

central cue.

Method

Participants.

Thirty new participants from Macquarie University completed Experiment 2 (8 male; $M = 22$ years, $SD = 5$ years). Six participants were excluded from the analysis due to technical difficulties during eye tracking (N = 3) or failing to make the correct saccade on more than 70% of trials (N = 3). In Experiment 2 we used the standard estimates from Experiment 1 as the basis of our power simulations (saccade congruency $b = .82$, cue validity, $b = .41$). Simulations with these estimates revealed power to be sufficient (80%) for an alpha level of .05 with 24 participants.

Stimuli.

In Experiment 2 the location of the saccade targets was indicated by three placeholder squares (3.04° x 3.04°) positioned 2.73° to the left, right and above the fixation circle (see Figure 4). Pilot testing revealed that once cue-target uncertainty was increased a mask was no longer necessary to reach 82% accurate performance, target offset was therefore not followed by a mask. Target location was cued by one of the placeholders turning pink.
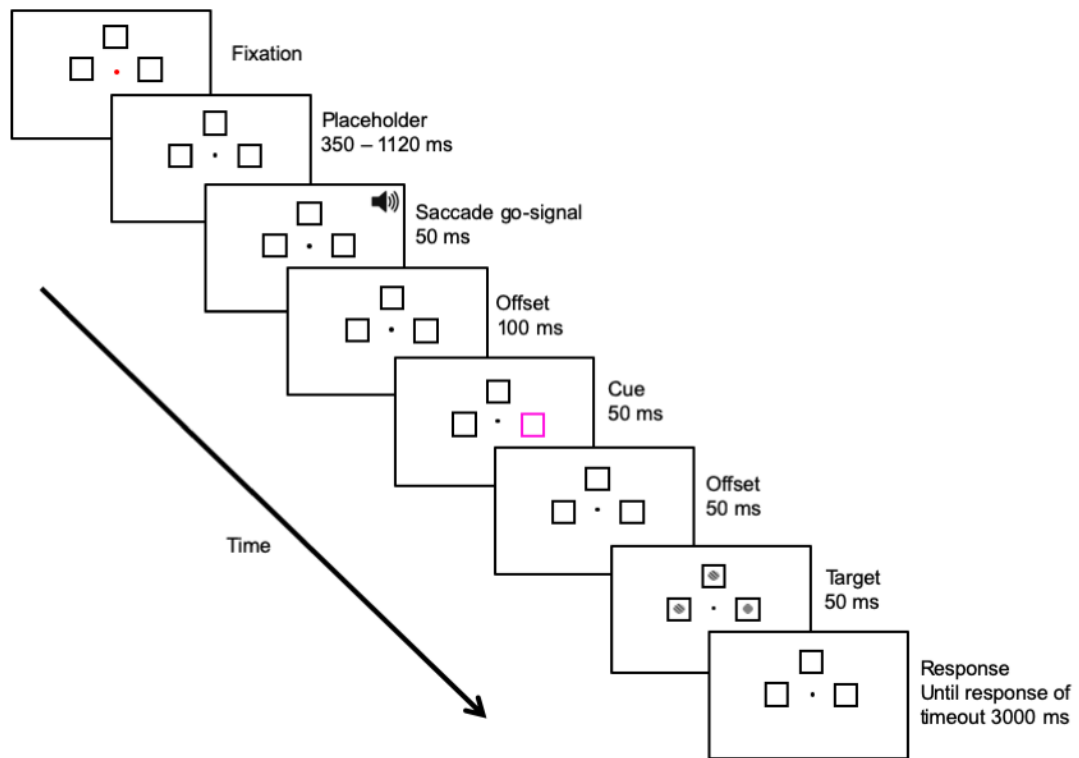
Figure 4. Trial structure for Experiment 2 valid trial.

Procedure.

Again, the experiment consisted of a training, staircase and main procedure, all following the same basic trial structure. Saccade instruction was blocked, such that at the outset of each block participants were told to saccade towards the left, right or up placeholder upon the onset of an auditory tone. These instructions were separated into three blocks and the order of blocks was counterbalanced across every 6th participant. Participants completed 252 trials per saccade instruction for a total of 756 experimental trials. The experiment followed a 3 x 3 factorial design where saccade congruency had three levels (congruent, incongruent-180° and incongruent-90°) and cue validity had three levels (valid, invalid-180°and invalid-90°). We excluded trials in which the target itself appeared in the "up" placeholder as these could not occur in the 180° condition. Therefore incongruent-180° trials were trials where the saccade goal was opposite the target (180°), and incongruent-90° trials were those where the saccade goal was at an angle of 90° from the target. Likewise, invalid-180° trials were those where the placeholder opposite the target was cued (180°), and invalid-90° trials were those where the placeholder at an angle of 90° from the target was cued. We selected an SOA of 100ms between cue-target onset in order to maximise peripheral cueing effects.[4]

Trial structure.

To begin the trial participants were required to maintain fixation on a small red fixation circle and press the space bar. In the first frame the red circle was replaced by a white circle, while the placeholder squares remained onscreen. The duration of the first screen was drawn randomly from an exponential distribution (minimum of 350ms). Ten

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[4] See supplementary materials for an analysis of manifest measures by absolute time bin.

percent of all trials were designated catch trials and were created by terminating trials in which the duration of the first frame exceeded 1120ms. Catch trials were included to ensure that participants had a flat hazard rate with respect to the beginning of the trial and the onset of the eye movement signal (Ghose & Maunsell, 2002). On all remaining trials an auditory tone played for 50ms. The tone signalled to participants to make an eye movement. After a further 50ms one of the three white placeholder squares was cued by drawing the outline in pink for 50ms. Each placeholder was equally likely to turn pink and the cue was non-predictive about the location of the target. The target, a horizontal or vertical Gabor patch, was then displayed after 50ms. The target could appear in any of the placeholder positions, and so was validly cued on one third of all trials. Distractors accompanied the onset of the target in the remaining two placeholder squares. Participants indicated whether the target was vertical or horizontal by pressing the up or down key, counterbalanced across participants, within 3000ms or the trial timed out. Again, two forms of feedback were given to participants.

Results

Manifest Analysis.

   Dual-task trials.

   Accuracy. An initial LMM excluding congruent and valid trials revealed accuracy not to vary by degree of visual angle. Given this, we restricted our analysis to 180° trials only. Ninety-degree and 180° trials were not collapsed across in order to ensure that the number of experimental trials in each condition was not disproportionate. We verified in a separate analysis that this decision did not substantially alter results. The modelling procedure including all remaining trials revealed that the inclusion of a main effect of both saccade congruency ($\chi^2(1) = 86.06$, $p < .001$) and cue validity ($\chi^2(1) = 60.01$, $p < .001$) improved the fit of the model. Accuracy was higher when saccade goal and target location were congruent ($M = 0.92$, $SD = 0.14$) relative to when they were incongruent ($M = 0.83$, $SD = 0.22$; $b = -1.01$, $SE = 0.11$, $z = -9.46$, $p < .001$). Similarly, accuracy was higher when the cue was valid ($M = 0.91$, $SD = 0.16$), relative to invalid ($M = 0.83$, $SD = 0.22$; $b = -0.81$, $SE = 0.11$, $z = -7.62$, $p < .001$) (see Figure 5A).

   Reaction time. Again, a preliminary analysis revealed RTs not to vary by degree of visual angle. Ninety-degree trials were therefore excluded. The modelling procedure of all remaining trials revealed the model of best fit to include an effect of saccade congruency ($\chi^2(1) = 165.63$, $p < .001$) and cue validity ($\chi^2(1) = 43.98$, $p < .001$). RTs were faster when the saccade goal and target were congruent ($M = 712$, $SD = 160$) relative to incongruent ($M = 787$, $SD = 182$; $b = 94.18$, $SE = 6.93$, $t = 13.59$). The same was true when the cue was valid ($M = 739$, $SD = 175$) compared to invalid ($M = 760$, $SD = 174$; $b = 46.02$, $SE = 6.92$, $t = 6.66$).

   Saccade latency. Unlike for accuracy and RT saccade latencies were found to vary by degree of visual angle. We therefore included all trials in our analysis of saccade latency. The

LMM revealed the model of best fit to include a Saccade Congruency x Cue Validity interaction ($\chi^2(1) = 113.31$, $p < .001$). This interaction is best characterised as a conflict effect, as can be seen in Figure 5C saccades were faster when directed towards the peripheral cue and slower when directed away from the cue. The size of this effect varied by degree of visual angle. Trials were therefore recoded to reflect whether the cue and saccade-goal were the same location, at an angle of 90° or 180°. Three FDR adjusted paired t-tests revealed that saccade latencies were fastest when cue-location and saccade goal was the same ($M = 400$, $SD = 42$) relative to when they were positioned at a 90° angle ($M = 415$, $SD = 45$; $t(23) = 4.36$, $p < .001$) or 180° angle ($M = 428$, $SD = 52$; $t(23) = 6.71$, $p < .001$). The difference between 90° and 180° trials was also significant ($t(23) = 3.82$, $p = .001$).
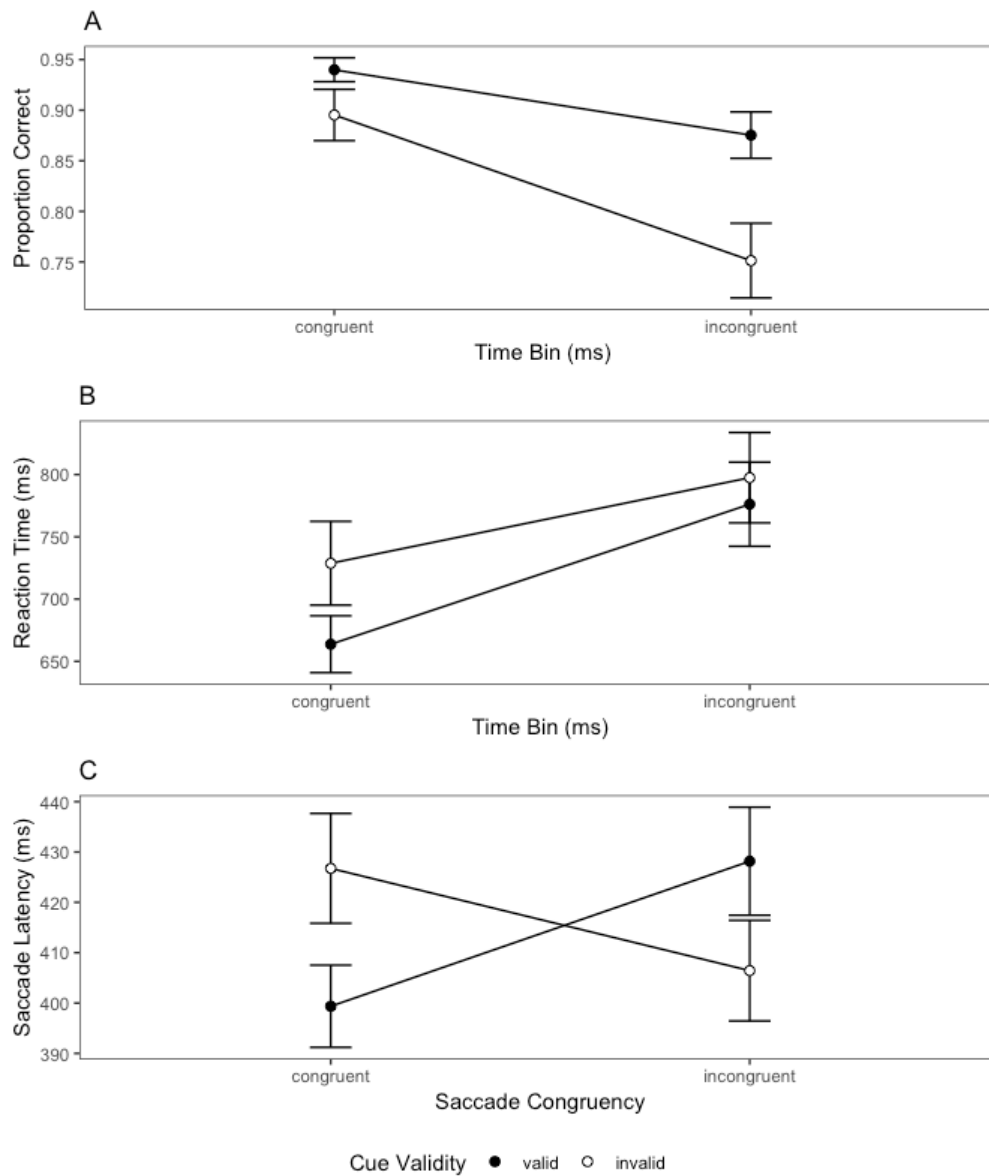
Figure 5. Experiment 2 mean (A) proportion correct, (B) reaction time and (C) saccade latency (ms) as a function of saccade congruency and cue validity. Incongruent trials are those where the saccade goal was directly opposite the target (180°) and invalid trials were likewise those where the placeholder opposite the target was cued (180°).

Linear ballistic accumulator analysis

   Model specification and fit.

   We fit an identical model to that outlined for Experiment 1 with one exception. Thresholds were allowed to vary by the new saccade instruction variable (left, right, up). As accuracy and RT did not vary by visual angle, we excluded 90° trials from our model fitting. Again, graphical summaries confirmed that the selected model was able to capture the trends in the data (see supplementary materials).

   Parameter estimates.

   Thresholds. The results of an LMM using thresholds as the dependent variable revealed the model of best fit to include an effect of response only, $\chi^2(1) = 5.14$, $p = 0.02$. Inspection of the standard estimates revealed thresholds to be significantly higher for responding vertical than horizontal ($b = 0.12$, $SE = 0.05$, $t = 2.31$). Thresholds did not vary by saccade instruction.

   Drift rate. An LMM with drift rate as the dependent variable confirmed that both saccade congruency ($\chi^2(1) = 16.87$, $p < .001$) and cue validity ($\chi^2(1) = 10.54$, $p = .001$) modulated the quality of evidence accumulation (see supplementary for full results). We therefore calculated a single index of quality by which to compare the relative magnitude of the saccade congruency and spatial cueing effects using the same procedure outlined for Experiment 1. As can be seen in the inset of Figure 6, while the size of the saccade congruency effect (1.16) was numerically greater than the magnitude of the spatial cueing effect (0.88) a paired t-test did not reach significance ($t(23) = 0.76$, $p = 0.45$).
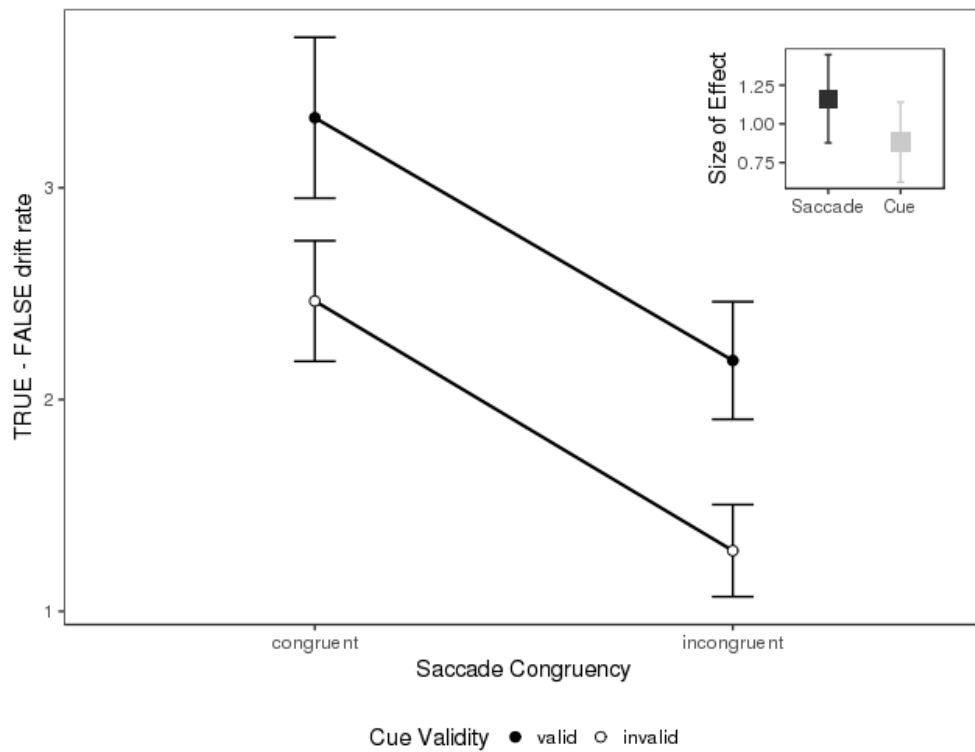
Figure 6. Difference between the true and false drift rates for saccade congruency and cue validity in Experiment 2. Inset shows the magnitude of the saccade congruency and spatial cueing effect did not significantly differ.

LBA analysis of saccade latency.

Model specification and fit. Analysis of latencies revealed the same interaction between saccade congruency and cue validity evident from Experiment 1, therefore we again fit an LBA model to each participant's saccade latency data using the same procedure. As saccade latency was found to vary by degree of visual angle, we included all trials in the fitting procedure. A preliminary analysis revealed eye movements towards the placeholder above fixation to be faster than saccades to the left or right placeholder, therefore we fit a model that allowed non-decision time and drift rate to vary by congruent, incongruent-180° and incongruent-90° trials where saccades were directed to the left or right visual field and congruent and incongruent-90° trials where saccades were directed to the placeholder above fixation. The priors and sampling procedure were identical to that outlined for Experiment 1. Again, model fit was good and CDFs are provided in supplementary materials.

Parameters. First, we report trials where the saccade goal was above fixation. Here, non-decision time was revealed to be 0.016s faster when the spatial cue also appeared above fixation, relative to when it appeared at an incongruent location, 90° from the saccade goal (0.176 s [0.172, 0.180] vs. 0.192 s [0.188, 0.196], $p < .001$). We then compared trials that required a left or rightward saccade. Again, non-decision time was found to be faster by 0.022s when the spatial cue and saccade goal were congruent, relative to 180° from each other (0.167 s [0.163, 0.170] vs. 0.189 [0.185, 0.193], $p < .001$). Finally, when both the spatial cue and saccade goal were incongruent non decision time was 0.008 s faster when these locations were at an angle of 90° relative to 180° (0.182 s [0.178, 0.185] vs. 0.189 s [0.185, 0.193], $p = <.001$). There was no difference in rates in Experiment 2.

Discussion

In Experiment 2 we sought to compare the magnitude of the saccade congruency and spatial cueing effect when a sudden onset/offset peripheral cue was employed. In addition, we also assessed the extent to which these effects were spatially distributed. That is, we compared performance on trials in which a saccade was required to a placeholder at an angle of 180° from the target (consistent with Experiment 1) with trials in which a saccade was required to a placeholder at an angle of 90° from the target. We also compared performance on trials in which the spatial cue appeared at these locations. The results of Experiment 2 establish that there is a quantifiable and independent contribution of spatial attention away from the saccade goal when a peripheral cue is employed. There is, however, no evidence to suggest that these effects are spatially distributed.

Consistent with Experiment 1, we observed an effect of saccade congruency and cue validity in accuracy. Unlike Experiment 1, however, these additive effects were also evident in RT. In saccade latencies there was again an interaction between saccade congruency and cue validity. When the evidence accumulation model was fit, the results revealed both saccade congruency and spatial cueing modulated the quality of information accumulation. Although the influence of saccade congruency was numerically greater than that of spatial cueing, a *t*-test did not reveal any evidence to suggest these magnitudes were significantly different. Quantifying orienting in the drift rate parameter of an evidence accumulation model, and specifically on the quality of information accumulation, enables the influence of spatial attention and saccade preparation to be compared across experiments. This type of evaluation revealed the saccade congruency effect to be 1.5 times greater in Experiment 2. The cueing effect, however, was over four times as large when a peripheral relative to a central cue was employed. We discuss these effects together with those in Experiment 1 in the general discussion below.

Interestingly we found no evidence to suggest that performance (accuracy or RT) was modulated as a function of whether a saccade was prepared away from the target and towards a placeholder at 90° or 180°. This was similarly true for trials in which spatial attention was captured at 90° and 180° from the target. These results suggest that the benefit of preparing an eye movement is confined to the saccade goal (Deubel & Schneider, 2003), and likewise the influence of spatial attention is specific to the cued location. In contrast to our finding in accuracy and RT, however, the size of the cue-saccade conflict effect in saccade latencies did vary by the degree of visual angle from the target. That is, eye movements were slower to initiate towards the saccade goal when it was directly opposite the cue compared to at an angle of 90° from the cue. This was true despite all placeholders being equidistant from the physical location of the eyes, fixation. Despite separating the spatial and saccadic cues, the conflict effect was still apparent in Experiment 2. Importantly however, unlike in Experiment 1 where this conflict effect was manifest in both non-decision time and drift rate, in Experiment 2 this effect was only found to manifest in non-decision time. This suggests that the conflict effect in saccade latencies cannot be attributed to an obligatory yoking between spatial attention and the preparation of an eye movement. Rather, conflict occurs during the motor execution of the eye movement, and may be best understood as a type of saccadic bottleneck.

General discussion

The aim of this study was to use computational modelling to isolate and quantify the influence of spatial attention and saccade preparation during dual-task performance. To this end, across two experiments we used evidence accumulation modelling together with a saccadic dual-task. Spatial attention was directed with either a centrally presented predictive arrow cue (Experiment 1) or a sudden-onset/offset peripheral cue (Experiment 2). Saccades were directed by blocked instruction. We used the quality of evidence accumulation as a common measure by which to compare the effects of spatial attention and saccade congruency. In doing so we were able to, for the first time, isolate the influence of orienting on decision making. This approach allowed us to unambiguously quantify the influence of spatial cueing and saccade congruency across blocked conditions and cue types. Our results establish that there is an independent and quantifiable influence of spatial attention away from the saccade goal, and that the magnitude of this effect varies depending on whether attention has been cued centrally or peripherally.

Magnitude of the saccade congruency and spatial cueing effects.

Across two separate dual-task experiments we found an effect of both saccade congruency and spatial cueing. Consistent with the dual-task literature performance was best when the discrimination target appeared at the goal of an upcoming eye movement (Castet et al., 2006; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Krajbich et al., 2010; Montagnini & Castet, 2007). Critically, there was also an effect of spatial cueing. That is, accuracy was better when the discrimination target was preceded by a valid, relative to an invalid spatial cue, consistent with a growing number of studies reporting an influence of spatial attention away from the saccade goal (Born et al., 2013; Castet et al., 2006; Deubel, 2008; Kowler et al., 1995; Moehler & Fiehler, 2014, 2015; Montagnini & Castet, 2007).

While these effects were apparent across both experiments, quantification revealed the relative contribution of spatial attention to vary by cue type.

      In an extension of previous studies, we used an evidence accumulation model to measure the influence of both spatial attention and saccade congruency. Unlike research analysing accuracy and response times, here we used the quality of information accumulation as a common measure by which to compare the contribution of each orienting mechanism. The results revealed that across both dual-task experiments, there was an independent and measurable contribution of saccade preparation and spatial attention, suggesting that spatial attention is not always obligatorily tied to the goal of an upcoming eye movement. The size of this influence however, was found to vary across experiments, presumably because of the difference in cue types. In Experiment 1 the results revealed saccade congruency to be a greater determinant of task performance than a centrally presented arrow. The saccade congruency effect in Experiment 1 was nearly four times as large as the cueing effect (0.78 vs. 0.20). The magnitude of both types of orienting were found to be greater in Experiment 2 (1.16 vs. 0.88).

      Importantly, using evidence accumulation modelling allows some of the differences between experiments to be accounted for by differences in model parameter estimates. For example, we are able to account for differences in response caution across Experiment 1 and 2 by allowing thresholds to vary. This means that the effects of response caution (which would indeed confound comparisons between experiments based on RT or accuracy) do not confound comparisons of drift rates. Drift rates themselves are affected by factors of interest, such as cue type, that vary across experiments. As a consequence, we are able to use this approach to assess how the contribution of spatial attention and saccade preparation differ across experiments. Interestingly, while the influence of saccade preparation was only about 1.5 times as large as that reported in Experiment 1, the influence of spatial attention was over

four times greater when directed by a peripheral, rather than central cue. This finding

suggests that the relationship between spatial attention and saccade preparation differs by cue

type. While previous studies have found the influence of spatial attention to vary by cue type,

these studies typically conclude that spatial attention and saccade preparation are flexible

when a centrally presented predictive cue is employed, but tightly coupled when a non-

predictive peripheral cue is used (Casteau & Smith, 2018; Smith, Rorden, & Jackson, 2004;

Smith, Schenk, & Rorden, 2012). Unlike these previous studies, we find that there is an effect

of spatial attention regardless of cue type, but that there is a much larger influence with a

peripheral cue.

It is possible that these magnitude differences arise because of the level of uncertainty

associated with each cue. The number of possible target locations differed across

experiments. In Experiment 1 the target always appeared at the goal of an arrow or directly

opposite it. In Experiment 2, on the other hand, the target could appear at any one of the three

possible placeholders. A larger influence of spatial attention in Experiment 2 may be because

this increase in target uncertainty led to a greater utilisation of the spatial cue. Similarly, the

difference in magnitude may be because in Experiment 1, unlike Experiment 2, the spatial

cue delivered information about both target location and the saccade goal. As participants

were required to interpret the spatial cue for saccade direction this may have obscured even

larger cueing effects in Experiment 1. It is important to note here, however, that while we are

inclined to attribute the magnitude differences to cue type specifically, we do not do so with

the intention to highlight possible differences between endogenously or exogenously oriented

attention. This is because it is now widely accepted that centrally presented arrows involve

both voluntary and reflexive shifts in spatial attention (Ristic & Kingstone, 2006; Ristic et al.,

2007). And, importantly, it was not the purpose of the present study to contrast the effects of

endogenous and exogeneous mechanisms.

Rather, and critically for our purposes, when the effect of covert orienting was isolated from other aspects of dual-task performance, we observed a unique and quantifiable influence of spatial attention away from the saccade goal. Thus, our results establish that saccade congruency and cue validity can both independently influence task performance. We now explore possible explanations for how this might occur.

One particularly longstanding debate in the literature concerns the extent to which shifts in spatial attention and the saccade congruency effect are the result of the same underlying mechanism or two distinct mechanisms. According to the first possibility, it is assumed that the mechanism which controls shifts in spatial attention is also responsible for the preparation and execution of an eye movement (Klein, 1980; Rizzolatti, Riggio, Dascola, & Umilta, 1987; Sheliga, Riggio, & Rizzolatti, 1994). Support for this proposition originally came from behavioural studies that found performance to be best at the goal of a saccade and unaffected by spatial cues (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Shepherd et al., 1986). Additional support has come from perturbation studies. In these designs stimulation of neurons within oculomotor structures such as the frontal eye fields (FEF) or the superior colliculus (SC) is found to also disrupt performance on tasks that engage spatial attention. These results have led authors to conclude that the neurons mediating saccadic planning are also responsible for controlling shifts in spatial attention (Cavanaugh & Wurtz, 2004; Grosbras & Paus, 2002; Moore & Fallah, 2001, 2004; Smith, Jackson, & Rorden, 2005).

However, more recent studies however have called into question this conclusion. Many behavioural studies, including the present study, now suggest that spatial attention can influence performance away from the saccade goal (Born et al., 2013; Castet et al., 2006; Deubel, 2008; Moehler & Fiehler, 2014, 2015; Montagnini & Castet, 2007). In addition, the results of single cell studies have called into question many of the conclusions drawn from

perturbation research (Sato & Schall, 2003). Neurons within the FEF, for example, have been found to have distinct characteristics. Some neurons are reported to be visual attention specific, others selective for oculomotor responses and others are reported to have both visual and oculomotor properties. Given this, it is difficult to establish whether perturbation of the FEF disrupts one or two distinct mechanisms. We interpret our results as evidence that spatial cueing and saccade congruency are mediated by two distinct underlying mechanisms. We base this conclusion on the finding that there is a measurable and distinct contribution of both spatial attention and saccade preparation. In particular, while the saccade congruency effect did not vary greatly between Experiment 1 and Experiment 2, the influence of spatial cueing did. If these two effects were mediated by the same mechanism then we would not expect the magnitude of this effect to vary by cue type.

This conclusion is further supported by the results of our saccade latency modelling. Analysis of saccade latencies revealed eye movements to be slower away from the spatial cue relative to towards it. A pattern of results that has previously been found for both centrally presented arrows and gaze cues (Hermans & Walker, 2012; Kuhn & Benson, 2007; Kuhn & Kingstone, 2009; Ricciardelli et al., 2002). Using an analysis of manifest measures, this could be interpreted as evidence that spatial attention and saccade preparation are obligatorily yoked. That is, slower latencies away from the cue may be because an eye movement is first programmed in the direction of the cue and then must be reprogrammed and executed towards the saccade goal. Evidence accumulation modelling allowed us to explore this proposition for the first time. In Experiment 1 modelling revealed the conflict effect to manifest in both non-decision time and drift rate, a finding which suggests that the conflict effect may be attributed both to a perceptual yoking between orienting mechanisms and also to a conflict in the non-decision aspects of the dual-task. This was possibly the case because

participants were required to interpret arrow direction for both target and saccade goal information.

We addressed the latter possibility in Experiment 2 by ensuring the cue and saccade instruction were orthogonal. Here the same conflict effect was evident in saccade latencies, but now only the non-decision time parameter of the model accounted for the effect. We interpret this as strong evidence that the conflict effect in saccade latencies cannot be attributed to an obligatory yoking between these two mechanisms. Instead, our preferred interpretation is that this conflict effect is due to a bottleneck in the saccade execution stage of dual-task performance. That is, when the cue location and saccade goal coincide saccade latencies are rapid. When, however, the spatial cue appears away from the saccade goal there is a conflict which must be resolved before a saccade can be executed. The conflict that arises when cue location and saccade goal do not coincide, therefore affects the execution of a prepared saccade but not the perception of the target.

While our results are consistent with the assumption that shifts in spatial attention and saccadic programming are mediated by two distinct underlying mechanisms, the results are also consistent with a "split spotlight" account. That is, our observed saccade congruency and spatial cueing effects could be accounted for by an account that posits a single mechanism that allocates spatial attention to two distinct locations in parallel. Consistent with this possibility, a number of studies have found that attention can be distributed to non-contiguous locations within a visual field (Awh & Pashler, 2000; Muller, Malinowski, Gruber, & Hillyard, 2003), including towards multiple saccade goals before eye movements (Baldauf & Deubel, 2008; Gersch, Kowler, & Dosher, 2004; Gersch, Kowler, Schnitzer, & Dosher, 2009; Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011). For example, Godjin and Theeuwes (2003) used a task that required participants to perform two saccades in succession and found that processing was enhanced at the goal of both saccades. According to this

account, the results of the present study would be due to spatial attention being allocated to both the saccade goal and spatial cue in parallel. Note, however, that it is not clear how this account could accommodate the observed magnitude differences evident across experiments. These findings, in contrast, more naturally follow from a distinct mechanism account of each type of orienting.

Discrimination-only trials

Finally, we measured the spatial cueing effect when participants were instructed to maintain central fixation (discrimination-only trials). It has previously been difficult to unambiguously compare the magnitude of these effects as it is typical for researchers to block discrimination-only and dual-task trials. Our results revealed the cueing effect on trials in which participants were instructed to maintain fixation to be almost five times the size of the cueing effect evident on dual-task trials. This finding is somewhat at odds with research that has reported saccade congruency effects to be larger than discrimination-only cueing effects (Hoffman & Subramaniam, 1995) and other studies that report the two to be of a similar magnitude (Montagnini & Castet, 2007). When participants are instructed to maintain central fixation the degree and direction in which a saccade is planned, but not yet executed, cannot be established. Despite this, in many cueing studies eye movements are typically minimized by excluding trials that contain explicit saccades or keeping the cue-target SOA shorter than the amount of time necessary to program and execute a saccade (~250 ms; Hallett, 1978). In this very typical design, the difference in performance between valid and invalid spatial cues is attributed to the operation of covertly oriented spatial attention. The results of the present study, however, revealed that the cueing effect on trials in which participants were instructed to maintain central fixation was greater than the spatial cueing effect obtained on dual-task trials. This finding calls into question what precisely is being measured in discrimination-

only cueing tasks. It is possible that the large cueing effect evident on discrimination-only trials is because participants, even when instructed to maintain central fixation, may nonetheless by preparing a saccade in the direction of the cue.

Conclusion

The degree to which spatial attention and saccade preparation are obligatorily yoked has been the topic of longstanding debate. Despite this, our understanding of the relationship between these two orienting mechanisms has remained largely the same as when researchers began investigating the topic (Hunt, Reuther, Hilchey, & Klein, 2019). Broadly, on one side of the debate is the view that the two orienting mechanisms are dependent and on the other side is the suggestion that they are independent. Part of the problem has been that until now there has been no conclusive way of measuring the relative contributions of both spatial attention and saccade preparation across blocked conditions, or across different dual-task designs. In this paper we used computational modelling to shed new light on the nature of this relationship. Using a common currency by which to compare the magnitude of these two orienting mechanisms our results revealed an independent and measurable influence of spatial attention away from the saccade goal. The magnitude of which was found to vary by cue type, with a peripheral cue influencing performance to a greater extent than a central arrow. These results are significant because they suggest that spatial attention and saccade preparation are mediated by distinct underlying mechanisms.

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